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MEASUREMENT OF FAST CRACK PROPAGATION IN GLASS UNDER DYNAMIC LOADING

W. Döll, M. G. Schinker and G. W. Weidmann*

INTRODUCTION

Determination of fracture toughness values under dynamic loading conditions is of considerable interest. Although various methods have been applied, the main problem in such tests has been the exact determination of the time-varying stress level responsible for the stress concentration at the crack tip. In this paper an experimental method is described which allows the stress to be determined not only at the onset but also during the whole period of rapid crack propagation. The method is applied to rapid crack propagation in glass and some novel environmental effects are reported.

EXPERIMENTAL TECHNIQUE

The experimental method is based on a drop weight apparatus which is shown schematically in Figure 1. The impact of the drop weight on the reflector plate produces a stress pulse which is transmitted via the rod and the lower grip to the specimen. The pulse amplitude and its variation with time are measured by strain gauges fixed to the specimen. To compensate for possible bending effects these are mounted on opposite faces. The length of the specimen and the location of the gauges are chosen so as to avoid interference between the primary stress pulse signal and those arising from reflections at the crack surface and the upper edge of the specimen. The amplified output of the strain gauge half-bridge is displayed on the oscilloscope which is triggered by the contact of the weight with the reflector plate (CT) via a delay line which compensates for the propagation time of the stress pulse in the rod. The loading rate depends on the experimental arrangement and specimen geometry and in this work was typically about 50 GPa s^{-1} with a rise time to maximum amplitude of about 250 μs.

In order to characterize the fracture process, and, in particular, to be able to calculate the value of the strain energy release rate G from the stress amplitude, it is necessary to correlate the stress σ with the crack length a, both as functions of time t. The dependence of the crack length on time was determined by ultrasonic modulation of the fracture surface using the method developed by Kerkhof [1]. Figure 2 shows an example of a glass fracture surface produced in this way with a frequency of 1 MHz. The two separately determined functions $\sigma(t)$ and a(t) were related to each other by arranging that the propagating crack interrupted a laser beam at a predetermined crack length a_m. This cut off the signal from a photodiode so that a time marker (LT) was produced on the second beam of the oscilloscope. Figure 3 shows an oscillogram from a fracture test on glass giving the stress pulse and the time marker. In relating the two functions $\sigma(t)$ and a(t) the time required for the stress pulse to travel

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*Fraunhofer-Gesellschaft, Institut für Festkörpermechanik, Rosastrasse 9, 7800 Freiburg im Breisgau, West Germany.

from the strain gauge to the crack plane was taken into account. It may be noted that using a 1 MHz modulation frequency provides a convenient method of determining the stress level at fracture initiation. Counting the number of ripple markings from the initiation crack length a_o to a_m gives the time in μs from fracture initiation to LT.

The experiments were preformed on long glass strips with typical dimensions $400 \times 50 \times 4$ mm^3 in the form of SEN specimens. Sharp edge cracks of various lengths were induced thermally and the specimens were conditioned for 48 hours in plastic bags containing different environments (ambient air, dry air, water and inert liquid).

RESULTS AND DISCUSSION

The results of crack speed measurements on glass plates dynamically loaded in ambient air are shown in Figure 4 as curves of crack speed v versus normalized crack length a/a_o. For comparison the corresponding curves for quasistatically loaded specimens are shown - where the quasistatic loading rates were such that the times to reach maximum load were of the order of a minute. It can be seen that for dynamic loading the acceleration of the cracks is higher and the maximum crack speed ($v \simeq 1500$ m/s) is obtained at lower values of a/a_o than in the case of quasistatic loading. Such a difference in behaviour, which can also be seen directly by comparing Figure 2 with Figure 5, was predicted theoretically by Berry [2] on the basis of an energy balance analysis of crack propagation in a specimen subjected to a greater than critical load. The reason for the difference here is that under the dynamic loading conditions the load increased during crack propagation whilst under the quasistatic loading conditions the load stayed practically constant. Dynamic corrections, such as that proposed by Broberg [3], apply equally to both cases and only produce a crack speed dependent shift in the curves.

Changing the environmental conditions of the specimens led to different crack propagation histories, even under dynamic loading conditions. As an example Figure 5 shows interferograms of ultrasonically modulated fracture surfaces of specimens dynamically loaded in dry air (r.h. ≃ 5%) and in water. The crack acceleration is significantly higher in the wet environment than in the dry. Thus, after the first modulation period (1 μs) in Figure 5 the crack in the water-conditioned specimen had reached a speed of about 1000 m/s whilst that in dry air had only reached about 10 m/s. These results are somewhat unexpected, especially in view of the well-documented slow crack propagation behaviour of glass [4, 5, 6] where it is generally accepted that at crack speeds in excess of about 1 m/s the behaviour is independent of environment. It should be borne in mind, though, that the results in this work are a reflection of initiation conditions rather than propagation conditions. Thus, a possible cause could be a blunting of the crack tip due to the corrosive action of water. However, control experiments on specimens immersed in an inert liquid (silicone oil) yielded results which were practically identical to those in water. This would seem to argue for a physical as opposed to a chemical origin for the phenomenon.

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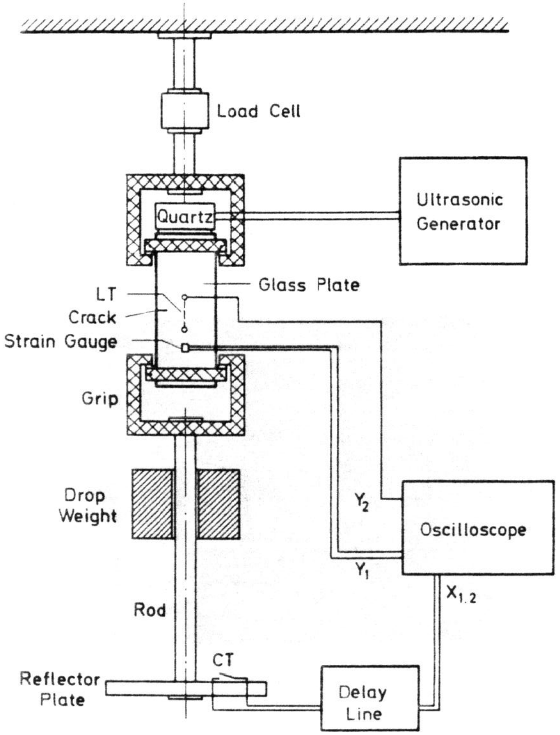

Figure 1 Schematic Representation of Dynamic Loading Apparatus
LT = laser trigger, CT = contact trigger

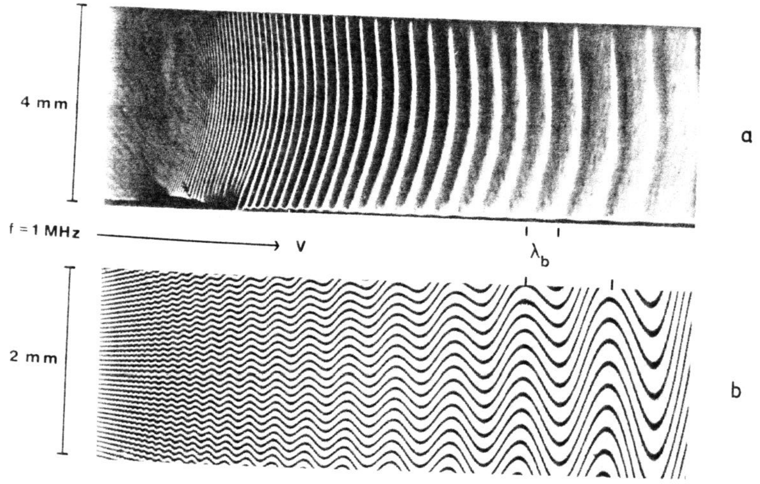

Figure 2 Fracture Surfaces Modulated by 1-MHz-ultrasonic Waves Under Quasistatic Loading Conditions (v = fracture velocity, f = ultrasonic frequency, λ_b = distance between successive ultrasonic ripple markings with $\lambda_b = v/f$)

(a) Reflection Schlieren Optical Micrograph
(b) Interference Optical Micrograph (λ_{light} = 0.540 nm)

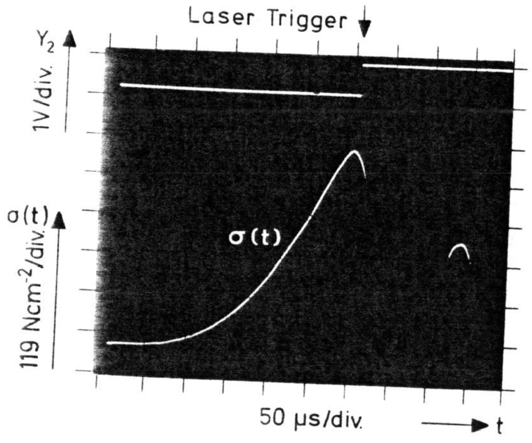

Figure 3 Fracture Test under Dynamic Loading Conditions, Lower Beam: Stress Pulse (119 Ncm^{-2}/div), Upper Beam: LT. Horizontal Deflection for both Beams 50 μs/div

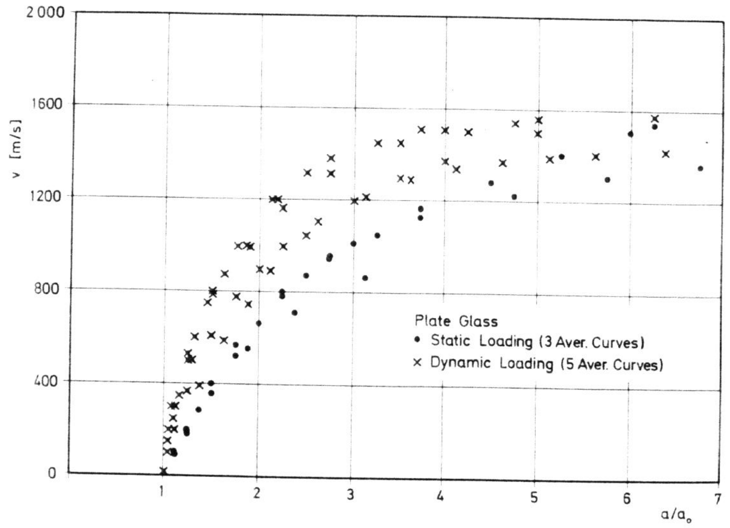

Figure 4 Crack Speed v as a Function of Normalized Crack Length a/a_o in Glass Under Quasistatic and Dynamic Loading Conditions

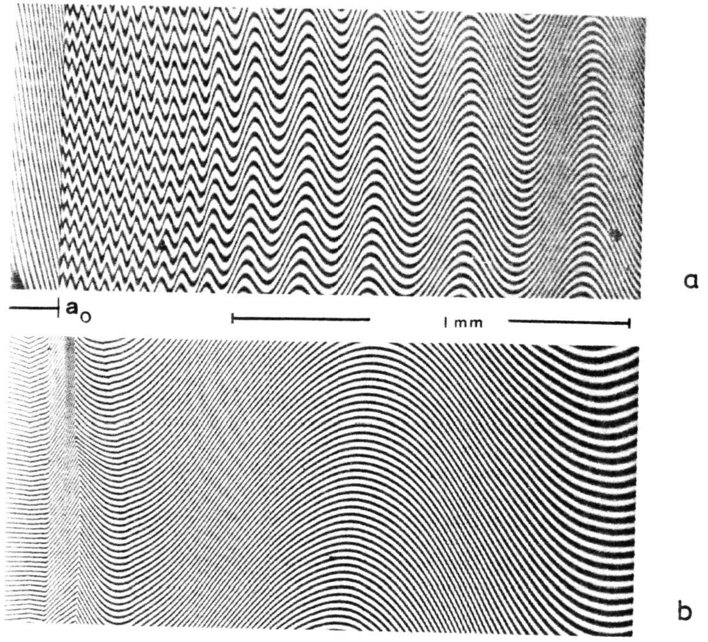

Figure 5 Effect of Different Environments on Fast Fracture in Glass Induced by Dynamic Loading
(a) Dry Air, (b) Water
(Ultrasonic Frequency 1 MHz; Interference Optical Micrograph)